

Numerical investigation of contact stresses for fretting fatigue damage initiation

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Numerical investigation of contact stresses for fretting fatigue damage initiation

N A Bhatti and M Abdel Wahab

Soete Laboratory, Faculty of Engineering and Architecture, Ghent University,
Technologiepark Zwijnaarde 903, Zwijnaarde B-9052, Belgium

E-mail: magd.abdelwahab@ugent.be

Abstract. Fretting fatigue phenomena occurs due to interaction between contacting bodies under application of cyclic and normal loads. In addition to environmental conditions and material properties, the response at the contact interface highly depends on the combination of applied loads. High stress concentration is present at the contact interface, which can start the damage nucleation process. At the culmination of nucleation process several micro cracks are initiated, ultimately leading to the structural failure. In this study, effect of ratio of tangential to normal load on contact stresses, slip amplitude and damage initiation is studied using finite element analysis. The results are evaluated for Ruiz parameter as it involves the slip amplitude which is an important factor in fretting fatigue conditions. It is observed that tangential to normal load ratio influences the stick zone size and damage initiation life. Furthermore, it is observed that tensile stress is the most important factor that drives the damage initiation to failure for the cases where failure occurs predominantly in mode I manner.

1. Introduction

Fretting is a surface damage due to a very small relative slip between two surfaces and can lead to fretting wear [1-4] or fretting fatigue [5-9]. The failure process in fretting fatigue is usually characterized by the initiation phase and propagation phase. Latter it has more sophisticated theories to study the process, whereas the intricacies involve in modelling of initiation phase still hampers to develop the consent among the researchers on best damage model. The problem perhaps stays in defining the point where initiation phase has been ended. In this paper, the term damage nucleation is used as the process of damage accumulation and the term damage initiation is used for a particular instant where micro cracks have started to develop [10].

Many researchers have proposed various methods and damage models to find damage initiation location and initiation life. Based on experimental study, Ruiz et al. [11] proposed two parameters to define damage initiation. The first parameter is termed as damage parameter $F1$ which is obtained by multiplying relative slip and shear stress. The second parameter is termed as initiation parameter $F2$, which is obtained by multiplying tensile stress with $F1$ parameter. Later, other researchers also used Ruiz parameters to model initiation behaviour in fretting fatigue. Kuno et al. [12] related the initiation parameter to fretting fatigue life. Nowell and Hills [13] explained the contact size effect on fretting fatigue lives. According to them the fatigue lives are inversely proportional to the contact width, even by keeping the stress level constant. As slip amplitude in partial slip is proportional to contact width, therefore they concluded that fretting fatigue life is dependent on slip amplitude.



Szolwinski and Farris [14] proposed a method by combining contact mechanics approach with multiaxial fatigue life parameters. With this approach they have observed crack initiation location at the trailing edge of the contact. Later, they showed comparison of experimental nucleation lives correlating well with the predicted method for aluminium alloy structural components [15]. Iyer and Mall [16] analysed the effect of contact pressure and stress amplitude on fretting fatigue lives. Their study revealed that amplification in local stress range is partly due to the normal load and partly due to compressive stresses during unloading. Furthermore, they showed fretting fatigue life decreases with increasing contact pressure alone. Lykins et al. [17] studied fretting fatigue crack initiation life for titanium alloy. Crack initiation location and lives are evaluated using strain based parameters, critical plane models and Ruiz parameter. They observed the damage initiation location is near the trailing edge of the contact, which is in agreement with the experimental results, however the results showed no specific correlation between $F2$ parameter and cycles to damage initiation.

This paper mainly focuses on application of finite element methods to explore damage initiation in fretting fatigue condition. The first portion presents the effect of tangential to normal load ratio (Q/P) on damage initiation location. In the second section the numerical results are combined with experimental results presented by Szolwinski and Farris [15], the relationship between initiation parameter and initiation life is studied. Also, the order of severity for internal stresses influencing the initiation life is analysed for the case where cracks grow under tensile stress or strain.

2. Experimental data and materials

Szolwinski and Farris [15] statistically designed experimental scheme to analyse the effect of different loads and pad radii to study fretting fatigue damage initiation. They studied contact under partial slip condition for the cylindrical pad and flat specimen. The normal load P is applied to maintain constant pressure. The cyclic axial load σ_A is applied to specimen and tangential load Q is generated through attached springs on the fretting pads. The configuration of experimental setup is shown in figure 1. Initiation life is determined from total number of cycles to failures and subtracting the propagation life. It is also pertinent to mention here that they computed the propagation life for 1mm crack length to the mid surface of the specimen.

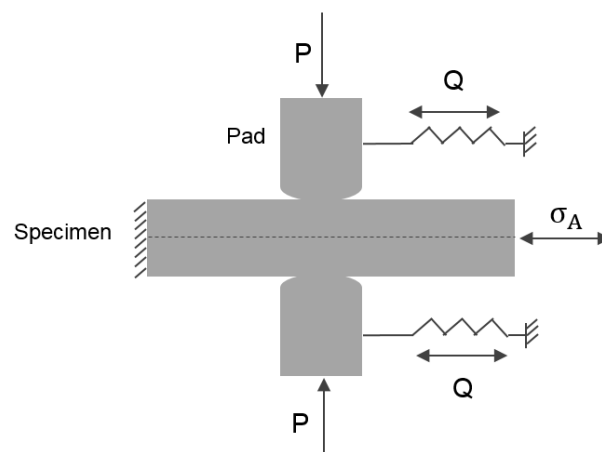


Figure1. Fretting fatigue test configuration

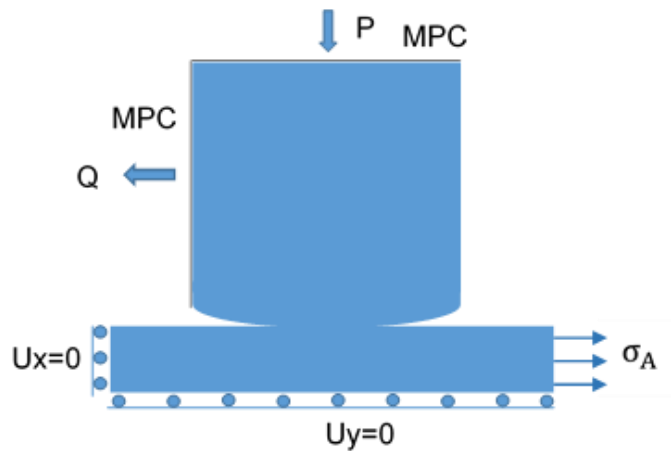
The data set used in this study is taken from the experimental data presented in [15]. Four selected experiments, shown in table 1, are used based on different Q/fP ratio (f is coefficient of friction). The pad radius selected is 178mm. The Aluminium 2024-T351 is used for both specimen and fretting pads. Poisson's ratio ν is 0.33 and modulus of elasticity E is 74.1 GPa.

Table 1. Experimental data from fretting fatigue test.

Experiment Number	P (N)	R (mm)	Q/fP (-)	σ_A (MPa)	$N_{i,exp}$ (cycles)	$N_{f,exp}$ (cycles)
1	7085	178	0.32	85.2	600638	665073
2	6176	178	0.42	84.7	555830	621442
3	6460	178	0.52	106.4	195200	225535
4	5319	178	0.55	97.4	418911	459882

3. Finite element model

Finite element analysis has been widely used in the literature for many engineering applications that have been recently published [18-31]. In this paper, the finite element model is generated using commercial software ABAQUS. The geometrical model including loads and boundary conditions is presented in figure 2. A constant normal load P is applied in the vertical direction at the top surface of the pad. Cyclic axial load σ_A is applied on one side of the specimen while the other end is restrained to move in horizontal direction. The bottom of the specimen is restricted to displace in vertical direction. To simulate the tangential load generated by the spring, Q is applied directly on one side of the pad. The value of coefficient of friction specified is 0.65. The master slave interaction algorithm is used to establish the contact between the pad and the specimen. The heights of 25mm and 6.35mm are used to model pad and specimen respectively. Thickness of both the fretting pad and the specimen is 12.7 mm. The lengths of fretting pad and specimen are 25mm and 40mm respectively.

**Figure 2.** Schematic of finite element model showing loads and boundary conditions.

To accurately model the high stress gradient effects at contact surface, mesh size of $5\mu\text{m}$ by $5\mu\text{m}$ is used at and near the contact region. The mesh size of $5\mu\text{m} \times 5\mu\text{m}$ is used, as some researchers [32] have modelled the fretting fatigue problem with reasonably accuracy. 4-noded bilinear elements CPE4R are used to mesh both parts using Plane Strain formulation. All the loads are applied in six steps for one complete loading cycle. The cyclic axial load σ_A and tangential load Q are applied in first step simultaneously, however the normal load is kept constant for all steps. Both the stress ratio R_σ and tangential load ratio R_Q are equal to -1. The finite element model is verified using half-space model for the data set of experiment 2. To satisfy the condition of half-space, the height of specimen modelled is $b=8.35\text{mm}$. The figure 3 shows the comparison of analytical and numerical profile for shear traction at the contact interface. For analytical solution readers are referred to [10]. The computed semi contact widths are $a_{\text{ani}}=1.67\text{mm}$ and $a_{\text{FEA}}=1.70\text{mm}$. It is observed that finite element solution matches well with the analytical.

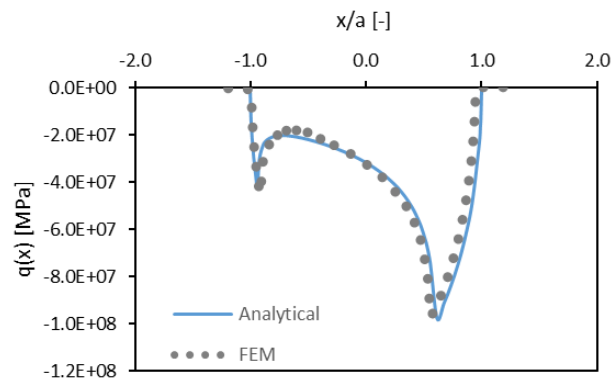


Figure 3. Comparison between analytical and FEM solution of shear traction $q(x)$ at the contact interface for Exp. 2 using half space model.

4. Results and discussion

The important factor which directly effects relative slip between contacting bodies is load ratio Q/fP . In the first section of the present study, the effect of variation of this parameter on damage initiation location is analysed using Ruiz parameters $F1$ and $F2$. Later variation of $F2$ with initiation life is presented.

4.1. Effect of Q/fP ratio

To analyse the effect of tangential to normal load ratio, data set of four experiments is used as stated in table 1. The coefficient of friction is kept constant at 0.65. Figure 4 shows the effect of variable Q/fP on stresses and damage parameters. From figure 4(a) it can be seen that the stick and slip zone widths change with changing load ratios. The magnitude of maximum shear traction and locations for maximum shear tractions are also different for all cases. For lower values of Q/fP , larger stick zone width is observed and vice versa. This implied that stick zone width is inversely proportional to Q/fP . However, peak of the shear traction is directly linked with the axial stress. The experiment with the highest value of applied axial stress has shown the highest peak for shear traction. Same is true for the tensile stress as depicted in figure 4(c). The normal stress directly depends on magnitude of normal load as shown in figure 4(b). The higher the magnitude of normal load, higher the normal stress is, whereas no uniform pattern is observed with Q/fP .

The relative slip is computed for each of the case and it is observed, in figure 4(e), that outside the stick zones the relative slip's amplitude increases with increase of Q/fP . It is also intuitive because higher tangential load will produce larger slip between the contacting bodies. The values of Ruiz parameters calculated are shown in figures 4(d) and 4(f) and for all cases peaks are observed at the trailing edge of the contact. Since the damage parameter is dependent on shear traction and relative slip, higher values of $F1$ and $F2$ are found for the experiment with larger shear tractions.

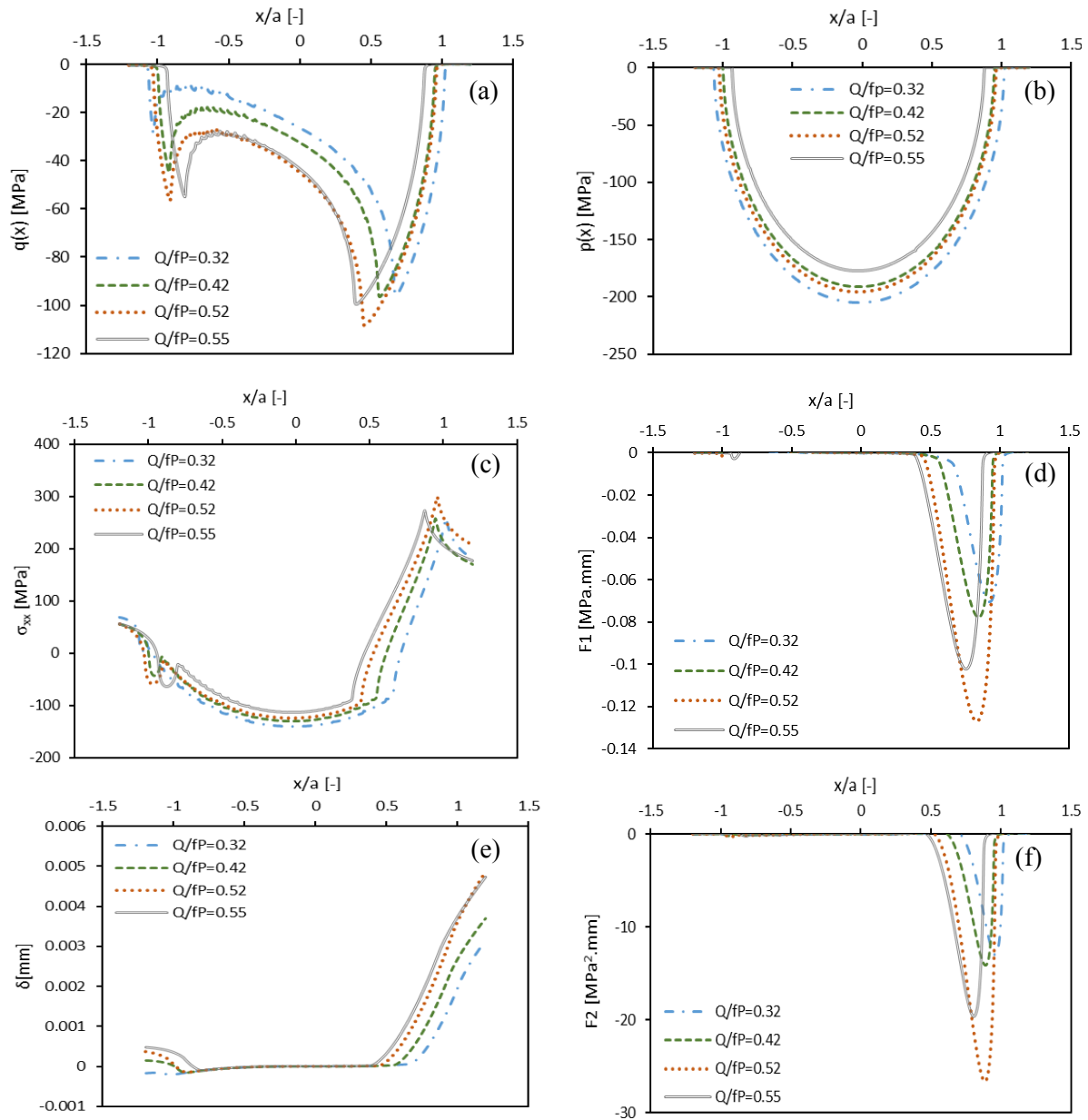


Figure 4. Effect of Q/fP on (a) shear traction $q(x)$, (b) normal stress $p(x)$, (c) tensile stress σ_{xx} , (d) Ruiz parameter $F1$, (e) Relative slip δ (f) Ruiz parameter $F2$.

Moreover, it is observed that for lower values of Q/fP , the initiation parameter is predicted more towards the trailing edge. Figure 5 shows the trend for variation of locations for maximum values of $F2$ parameter, normal stress, tensile stress and shear traction against Q/fP . It can also be interpreted that the magnitude of damage and initiation parameters are dependent on individual loads whereas the location is dependent more on the ratio Q/fP .

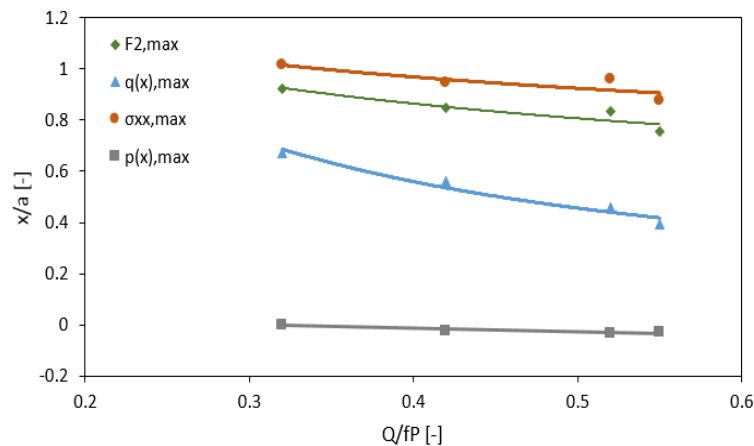


Figure 5. Variation of peak stresses and $F2$ parameter with Q/fP .

4.2. Variation of initiation life with initiation parameter

In this section, the results of the current numerical work are combined with the experimental results from literature. The stresses shown above are computed at the contact interface only, as in fretting fatigue damage initiates at the surface. It is observed that when the initiation parameter $F2$ is higher, the number of cycles to initiation is lower. It is also logical and intuitive to expect the decrease in damage initiation life on increase of damage parameter. The variation of $F2$ parameter versus cycle to initiation is presented in figure 6(a). However, this trend may be dependent on material properties. Lykins et al. [17] used this parameter for titanium alloy Ti-6Al-4V and they found no specific correlation between $F2$ parameter and number of cycles to initiation. Figure 6(b) shows the relationship between peak stresses and number of cycles to initiation. For cases with higher number of cycles to initiation, lower value of shear tractions and tensile stresses are observed while no specific trend is observed for normal stresses. For comparison purposes absolute values are plotted for each case. It is observed that for all experiments normal stresses are higher than shear tractions and tensile stresses are higher than normal stress.

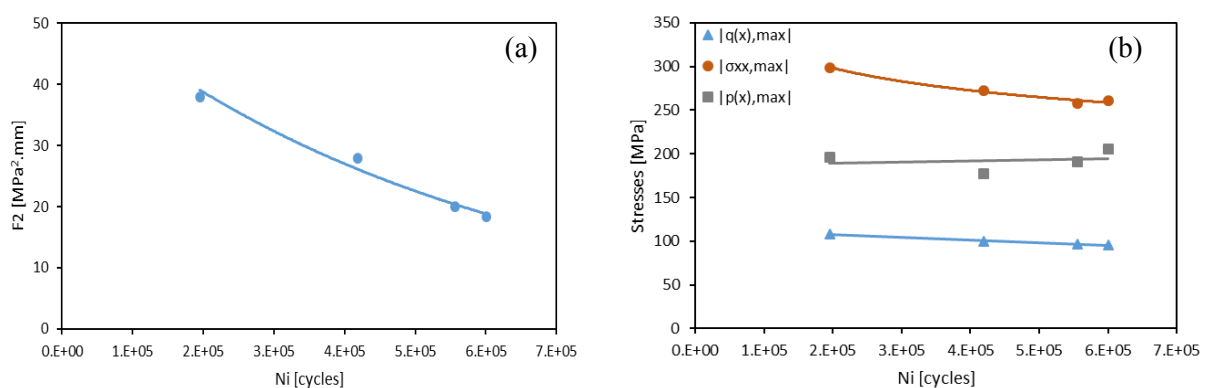


Figure 6. Variation of number of cycles to failure with (a) $F2$ parameter (b) absolute value of maximum tensile stress σ_{xx} , normal stress $p(x)$ and shear traction $q(x)$.

Considering the above discussion and the experimental results presented in [15], where it is shown that the failure occurred in the direction perpendicular to the specimen axis, it can be concluded that the peak in the tensile stress at the trailing edge of the contact is the primary reason that energies damage initiation to failure for the cases where failure occur in classical mode I manner.

5. Conclusion

In this paper various factors have been analysed, affecting the fretting fatigue damage initiation location. Based on the results presented above, following points can be concluded.

- In fretting fatigue configuration, damage initiation is dependent on Q/fP ratio. When Q/fP ratio decreases, the stick zone size increases and the initiation location shifts more towards the trailing edge of the contact.
- The peak of the shear traction and tensile stress is directly linked with applied axial stress. The higher the values of applied axial stress, the higher the values of shear traction and tensile stress.
- Results suggest that, higher the value of fretting fatigue damage initiation parameter $F2$, the lower number of cycles are required for damage initiation and vice versa.
- The magnitude for tensile stresses is much higher than shear and normal stresses for any particular case. Therefore, the most damaging stress for failure is tensile stress, then normal stress and the least effect is expected for shear traction.

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